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Research Paper

Flow patterns and heat transfer characteristics of flat plate pulsating heat pipes with various asymmetric and aspect ratios of the channels

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HIGHLIGHTS

- Flat plate pulsating heat pipes with asymmetric and aspect ratios were tested.
- Flow patterns were investigated according to channel geometry and flow condition.
- Heat transfer characteristics were analyzed with various heat inputs.
- Optimum asymmetric and aspect ratios were suggested for maximum thermal performance.

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ABSTRACT

The thermal performance of flat plate pulsating heat pipes (PHPs) in compact electronic devices can be improved by adopting asymmetric channels with increased pressure differences and an unbalanced driving force. The objective of this study is to investigate the heat transfer characteristics of flat plate PHPs with various asymmetric ratios and aspect ratios in the channels. The thermal performance and flow pattern of the flat plate PHPs were measured by varying the asymmetric ratio from 1.0 to 4.0, aspect ratio from 2.5 to 5.0, and heat input from 2 to 28 W. The effects of the asymmetric ratio and aspect ratio on the thermal resistance were analyzed with the measured evaporator temperature and flow patterns at various heat inputs. With heat inputs of 6 W and 12 W, the optimum asymmetric ratio and aspect ratio for the flat plate PHPs were determined to be 4.0 and 2.5, respectively. With the heat input of 18 W, the optimum asymmetric ratio and aspect ratio were determined to be 1.5 and 2.5, respectively.

1. Introduction

Thermal management of electronic devices has become an important issue due to higher chip density. Many researchers have proposed various cooling methods for effective thermal management of compact electronic devices [1–7]. A heat pipe is considered an effective cooling method due to its higher thermal performance with no power consumption [8–13]. However, the conventional heat pipe cannot always show excellent thermal performance in compact electronic devices due to limitations on miniaturizing the cooling unit. A pulsating heat pipe (PHP) that consists of multiple capillary U-turn tubes has been adopted in electronic cooling systems because of its high cooling performance and simple structure without a wick. In the PHP, the heat transfer occurs effectively with the help of pulsating or circulating motion of a working fluid. With the increased demand for high performance electronic devices, the PHP with more efficient cooling capability is needed. However, there are still few studies on the fundamental working mechanism and heat transfer characteristics of the PHP. More comprehensive research is needed to predict the optimum geometric design of channels and number of turns in the PHP. In addition, a novel channel design is required to enhance the driving force of the PHP to achieve consistent performance in any orientations.

The thermal performance of a PHP is affected by various design parameters: internal diameter, number of turns, working fluid, and inclination angle. The thermal performance increases with an increase in the internal diameter. A certain critical number of turns was suggested to achieve proper performance according to the internal diameter and operating orientation [14–18]. Han et al. [19] reviewed the development of a PHP based on the summary of the latest literatures. Both experimental and theoretical studies for the PHP were summarized and potential applications of the PHP were also reported. For effective cooling applications in a thin

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Nomenclature

A	heat transfer area (mm^2)
A_c	cross-sectional area (mm^2)
d	depth of channel (mm)
D	diameter (mm)
f	improvement ratio
f_D	friction factor
F_{fl}	fluid dependent parameter
G	mass flux (kg m^{-2} s^{-1})
h	heat transfer coefficient (W m^{-2} °C^{-1})
h_{fg}	latent heat (J kg^{-1})
k	thermal conductivity (W m^{-1} °C^{-1})
L	length (mm)
$\dot{m}$	mass flow rate (kg s^{-1})
N	number of channels
p	pressure (N m^{-2})
Pr	Prandtl number
q''	heat flux (W m^{-2})
Q	heat input (W)
R	thermal resistance (°C W^{-1})
t	thickness (mm)
T	temperature (°C)
U	overall heat transfer coefficient (W m^{-2} °C^{-1})
V	velocity (m s^{-1})
V_{int}	internal volume of PHP (mL)
w	width of channel (mm)
x	mass quality

Greek symbols

θ	contact angle (°)
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
ϕ	ratio

Subscripts

asp	aspect
asym	asymmetric
c	condenser
e	evaporator
l	liquid phase
sym	symmetric
TP	two-phase
v	vapor phase

and small electronic device, PHPs have been developed in the form of a flat plate heat spreader in which closed-loop channels are designed with a serpentine shape. Yang et al. [20] reported that the operating characteristics of flat plate PHPs varied according to the cross-sectional shape under the same hydraulic diameter and filling ratio. Youn and Kim [21] and Qu et al. [22] measured the thermal characteristics of silicon-based micro PHPs by varying the filling ratio, inclination angle, and heat input.

Novel channel designs in PHPs have been proposed to improve the thermal performance. Chien et al. [23] suggested an asymmetric channel design for the first time and compared the thermal performance of a flat plate PHP with a non-uniform channel with that of a flat plate PHP with a uniform channel according to the heat input and filling ratio in both vertical and horizontal modes. Tseng et al. [24] investigated the effects of non-uniform tube diameters on the thermal performance of PHPs. The alternating tube diameter allowed for an early working of pulsating motion with lower thermal resistance. Kwon and Kim [25] investigated the operating characteristics of PHPs with a dual-diameter tube and proposed an optimum ratio of the diameter difference to the average tube diameter in which the thermal performance was maximized. Yang et al. [26] investigated the effects of thermophysical properties of the working fluids (water and methanol) on the thermal performance of fabricated micro PHPs with alternate microchannel widths.

The thermal performance of flat plate PHPs with asymmetric channels is strongly dependent on the asymmetric ratio in alternate channels and the aspect ratio of the width to the depth of the channel cross section. Therefore, both the asymmetric ratio and the aspect ratio have to be considered important design parameters. Asymmetric channels in flat plate PHPs need to be designed optimally according to its applications. However, systematic approaches on the thermal performance of flat plate PHPs with asymmetric channels according to the asymmetric ratio and aspect ratio are very limited in open literature. The objective of this study is to investigate the heat transfer characteristics of flat plate PHPs with various asymmetric ratios and aspect ratios in the channels. The thermal performance and flow pattern of the flat plate PHPs with asymmetric channels were measured by varying the asymmetric ratio, aspect ratio, and heat input. The effects of the asymmetric ratio and aspect ratio on the thermal resistance were analyzed with the measured evaporator temperature and flow patterns at various heat inputs. In addition, the optimum asymmetric ratio and aspect ratio for the flat plate PHPs with asymmetric channels were proposed to improve the thermal performance in various geometric and operating conditions.

2. Experimental setup and test procedure

2.1. Experimental setup

Fig. 1 shows a schematic diagram for the experimental setup. The thermal load in the evaporator section was controlled by a polyimide heater. A thin aluminum block was inserted between the heater and the PHP plate for uniform heat distribution. A thermoelectric cooler was used to dissipate the heat in the condenser section. The temperature in the condenser section was controlled by adjusting the power input to the thermoelectric cooler. The areas of the heating and cooling sections were the same at 25×54 mm^2. For flow visualization, transparent quartz glass was used at the top of the test section, which was insulated using a transparent polycarbonate cover. The sealing between the quartz glass and the PHP plate was done by using O-ring. Silicone OCA (optically clear adhesive) was used for sealing between the channels. The vacuum level was checked for 24 h before the test.

Fig. 2 shows the PHPs with symmetric and asymmetric channels. The channels of the PHPs were fabricated on STS plate by etching. The overall size of the PHPs was 70×120 mm^2. Table 1 shows the specifications of the PHPs. The asymmetric ratio was varied from 1.0 to 4.0 and the aspect ratio was varied from 2.5 to 5.0. As given in Eq. (1), the asymmetric ratio of the channels was defined as the ratio between the cross-sectional areas for the alternate channels. As given in Eq. (2), the average aspect ratio of the channels was defined as the ratio of the average width to the depth in the channel cross section.